FLUVIAL DYNAMICS AND THE EFFECTS OF GLEN CANYON DAM ON THE GEOMORPHOLOGY OF THE COLORADO RIVER IN THE GRAND CANYON.

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ABSTRACT

The Colorado River in the Grand Canyon slopes from an elevation of 1000 m near Lees Ferry, Arizona, to less than 300 m at Lake Mead, 450 km downstream. The 161 rapids along the route are responsible for most of the elevation change. Alluvial fan boulders deposited by side-canyon tributaries have been reworked to form the rapids. Because of a fourfold reduction of peak discharge caused by Glen Canyon Dam, new fan debris may increase the gradient through some of the rapids by a factor of 1.8.

Before the construction of Glen Canyon Dam, sandy bed deposits underwent seasonal scour and fill. The average scour was about 1 m during spring floods, balanced by deposition during the summer. Decreased turbulence in the rapids since the dam has resulted in deposition averaging 2.2 m.

The addition and removal of sediment in each size range is approximately balanced. The time scale for equilibrium of the fan deposits is tens of thousands of years, for cobbles thousands of years, and for the sand bed deposits and banks, a few months.

Rivers adjust in order to transport sediment with greatest efficiency; however, due to the morphological constraints imposed by the bedrock channel in the Grand Canyon, the tributary fans, and the cobble bars, the Colorado River is overefficient with respect to the transport of sand, the dominant component of the sediment load.

INTRODUCTION

In a previous paper (Howard and Dolan 1980), we outlined the morphology and sedimentology of the fluvial deposits of the Colorado River within the Grand Canyon. They are composed of three grain-size ranges sorted into distinct deposits:

1) lag deposits of alluvial fan boulders at the junction of tributaries with the main-stem bars;

2) riffles of cobbles and pebbles in transport through the canyon, and;

3) terrace, bank, and bed deposits of sand (and locally silt and clay) deposited by the abundant suspended sediment load.

In this paper we extend this research to explore the budget of supply and removal of these fluvial deposits, and consider the time scales of supply and removal equilibrium and the influence of Glen Canyon Dam (completed in 1964) upon this balance.

The effect of the dam has been different for the three types of deposits. The cobble bars, moved by only the largest floods before the dam, are now immobile. The tributary fans are locally accreting due to side-canyon flooding. And contrary to our initial expectations, more sand has accumulated within the channel than has been removed since regulation of the river began. This post-dam storage, which is opposite to predictions based upon the application of sediment transport formulas (Laursen et al. 1976) is apparently due to the lack of large spring flood peaks which prior to the dam scoured the fine sediment.

Scour and fill in most sandbed channels result from local redistribution of bed sediment. Most fluvial investigators feel that appreciable short-term scour and fill over long reaches is uncommon. However, within the Colorado River from Cisco, Utah, to Lake Mead (fig. 1), we find evidence of synchronized scour and fill along this 650 km of channel. The scour and fill is most pronounced within the Grand Canyon section of the river, where the profile is steep and boulder-floored rapids alternate with sand-bedded pools. Turbulence within the rapids during spring flood peaks caused a scour averaging as much as 1.5 m along the entire canyon section. This was balanced over the long run by summer and fall sediment contributions of desert runoff.

In our investigations of the Colorado River within the Grand Canyon we find a separate equilibrium for each of the dominant grain sizes, each with a characteristic time scale. The river adjusts for optimal transport of sand only within constraints imposed by the boulder rapids, the gravel riffles, and the bedrock-constrained channel width.

DYNAMICS OF FLUVIAL DEPOSITS

In their natural state, the three grain sizes of the Colorado River fluvial sediments (alluvial fan boulders, cobble bars, and fine sediment) have distinct sources, sinks, and dynamics. Each has responded in a different manner to the imposition of Glen Canyon Dam.

Alluvial Fan Boulders. Because the coarsest debris brought by tributary floods cannot be transported by the Colorado River at gradients characteristic of between-rapids reaches and pools, large debris floors the river only in the rapids. This implies that the quantity of debris supplied by tributaries is too little to force the entire river into a gradient steep enough to transport coarse material through the Grand Canyon. However, sufficient quantities are supplied to account for the elevation losses through the rapids that dominate the gradient of the river. Addition of debris by floods should, therefore, be balanced over time by its removal after comminution by abrasion, breakage, or solution (Schumm and Stevens 1973, discuss size reduction of coarse debris in place). The size of debris flooring a given rapid is determined by several factors including the size and quantity of the debris supplied, the maximum main-stem, post-depositional flood peaks, and the local river width (the river has greater competence where tightly constricted). Fine detritus is sorted out, leaving a pavement of the coarsest debris delivered in sufficient quantity to form a coherent bed.

Side-canyon floods merging into the main canyon lose competence and deposit their coarse debris as a relatively localized obstruction across the main channel. The mainstream flows rework this debris, sorting and removing the finer detritus, widening the river, and reducing the gradient to a value consistent with the threshold of motion of the coarsest debris. Because the competency of the river increases with stage, the maximum flood-stage discharges should have determined the channel gradient and width

through the debris fans. Due to their erosional origin, channel cross sections through the fans should have the minimum width consistent with bed and banks of fan debris. Graf (1979) cites evidence of the bare competence of flood peaks to transport the fan debris and the relative immobility of the coarse lag boulders.

The multifold reduction of maximum post-dam flood peaks from 3,400 m^3/s to 850 m^3/s raises the possibility that rapids in tributary fans may increase in gradient and decrease in width if side-canyon flooding adds new debris. Formulas for threshold-of-motion channels in coarse debris presented by Henderson (1966, p. 454) suggest that a fourfold reduction in peak discharge could allow an increase in rapid gradients by a factor of 1.8 under such circumstances (assuming no change in fan debris size). This raises the possibility of future creation of rapids too steep for navigation by float trips (Dolan et al. 1974). The intense tributary flooding in December, 1966 (Cooley et al. 1977) added debris to many tributary fans, steepening rapids and narrowing the channel; one of those rapids most severely affected, Crystal Rapids (mile 98), is now barely navigable.

Cobbles. Although cobble-sized detritus forms a conspicuous component of the fluvial deposits in the Grand Canyon, it is poorly represented downstream in the deposits of Lake Mead (Smith et al. 1960). Cobbles are a relatively slow-moving component of the sediment load. In fact, they are immobile under the present controlled flow regime and were moved by the largest pre-dam flood peaks. Cobbles are abundant in the lower portions of the channel bed fill but are usually covered by 2-6 m of sand (Bureau

of Reclamation 1950, 1970; Pemberton 1976). Thus these cobbles can be moved only during flood peaks when the overlying sand has been scoured.

Cobble bars are most prevalent in the widest portions of the canyon where flood-stage tractive forces are the lowest. This concentration of cobbles in wide portions of the river is analagous to a high density of cars on the portions of a freeway where traffic is moving slowly (Langbein and Leopold 1968). Cobble-sized debris is a through-flowing component of the sedimentary load, as is attested by well-rounded shapes partially derived from far upstream, but primarily from in-canyon sources, particularly through selective removal from the debris fans.

The cobble bars are well-sorted and vary in grain size from pebbles to cobbles averaging more than 1/3 m in size. The larger cobbles are presently immobile but smaller pebbles are probably still in motion locally on the channel bed. Under pre-dam conditions, much debris that would be added to the cobble component by selective sorting of new fan deposits and by comminution of older fan boulders, now remains on the fans. Because of their large size and sedimentary composition the cobbles should be rapidly comminuted by solution, breakage, and abrasion. Thus individual cobbles may not, in general, move the length of the canyon before being reduced to sub-cobble size. Thus comminution is a contributing factor to the poor representation of cobbles in Lake Mead sediments.

Fine-Grained Sediment. The sand-sized and finer sediment transported by the Colorado River is the most important size range both in terms of the extent of deposits and its relative abundance

in the sediment load (>99% of the total load). Furthermore, the fine-grained sizes are the most conspicuously affected by Glen Canyon Dam.

The sedimentary budget of this component is well documented by suspended sediment concentration measurements starting in 1922 on the main stem of the Lees Ferry and Grand Canyon gaging stations and from 1948 through 1970 on the major tributaries (the Little Colorado River and the Paria River) (fig. 1). Therefore our discussion of the sediment budget of the fine-grained sediment forms the bulk of our presentation.

The Colorado River is a suspended load river; that is, most of the sediment in the size range characteristic of the channel bed is carried in suspension, at least at high flows. For example, about 30 percent of the sediment transported during pre-dam spring flood peaks was as coarse as the size range of the bed sands (>.1mm). As a result of the dominant role of suspended load transport and the normally high sediment concentrations of the river, the sandy deposits of the bed, banks, and terraces were and are subject to continuous reworking in response to changes in flow conditions, serving as both source and sink of sand and coarse silt. The dynamic character of the sandy deposits is illustrated by the large magnitude of scour and fill (up to 1.5 m in average bed elevation; larger for local bed elevation) that occurred at the Grand Canyon and Lees Ferry gaging stations in response to seasonal and long-term variation of discharge and sediment load (figs. 2 and 3).

By contrast, fine silt and clay-sized components of the sediment load are carried as wash load, generally being transported

through the canyon without deposition, except in the very still-water environments.

Prior to construction of Glen Canyon Dam, additions from tributaries below Lees Ferry accounted for only 20.4 percent of suspended sediment load at the Grand Canyon gaging station. Because of the dramatic reduction of sediment load caused by the construction of the dam, Dolan et al. (1974) and Laursen et al. (1976), predicted that net scour of the bed and widespread net erosion of the terraces would result. However, our detailed analysis of the post-dam sediment budget does not confirm these expectations. Since flow regulation, net deposition has occurred primarily on the channel bed although this has been accompanied by a slight net lateral erosion of sandy beaches (Howard and Dolan 1979). The documentation and explanation of this aggradation requires an analysis of the pre-dam sediment budget and the nature of the alteration in transport regime brought about by the dam.

Pre-dam Sediment Budget --During the decade 1948-57, prior to appreciable influence from construction or operation of Glen Canyon Dam, detailed sediment records were collected at the head and end of an 87-mile segment of the Colorado River between the Lees Ferry and Grand Canyon gaging stations (this river segment is called the Upper Canyon). In addition, sediment records were collected on the Paria River just upstream from its junction with the Colorado, and on the Little Colorado at Cameron, 26 miles upstream from the Colorado River. Table 1 summarizes the sediment yield and drainage area characteristics of these tributaries, the main stem, and the ungaged tributaries of the Colorado River in

Utah and Arizona. A detailed input-output balance of the sediment budget of the Upper Canyon was conducted using monthly totals of water and sediment discharge. Net storage change, ΔS (measured in metric tons), occurring within the reach during a given time interval is equal to the difference between inputs and output. A simple model of this budget is:

$$\Delta S = LF + LC + PR + M(LC + PR) - GC, \tag{1}$$

where LF, LC, PR, and GC are sediment loads of the Lees Ferry, Little Colorado River, Paria River, and Grand Canyon gaging stations, respectively. The contribution of the ungaged tributaries is estimated by multiplying the measured tributary inputs by a weighting factor, M. Although the estimated sediment yield of ungaged tributaries may result in appreciable error for individual runoff events, it becomes more accurate for monthly and yearly yields for the proper value of M.

The weighting factor can be estimated by assuming an appropriate sediment yield by comparison with similar gaged tributaries or alternately by assuming a value which gives the best comparison with observed scour and fill behavior of the Grand Canyon and Lees Ferry gaging stations. Equating the sediment yield of the ungaged tributaries with those of the Little Colorado River, the Paria River, and Kanab Creek (a tributary which enters below the Upper Canyon) gives values of the weighting factor of .05, .34, and .13, respectively. As will be discussed more fully below, the best matching of scour and fill of the Grand Canyon gaging station occurs for a value of M in the range of .30 to .35, implying sediment yields of about 776 metric tons/km-yr for the

ungaged tributaries (table 1). This relatively high estimate
seems reasonable, due to the very steep relief and sedimentary
geology of much of the ungaged drainage area.

Storage changes were estimated on a yearly basis in a
similar manner for two reaches of the Colorado River above Lees
Ferry, however availability of sediment load records limited these
estimates to the years 1949-1958. The lower reach (Reach 2)
extends to Lees Ferry from Hite, Utah, approximately 163 miles
upstream, and includes measured input from the San Juan River,
the Colorado River upstream from Hite, and unmeasured contributions
from 21,500 km^2 (fig. 1 and table 1). The upper reach (Reach 1)
extends from Cisco, Utah on the Colorado River and from Green
River, Utah to Hite (about 151 miles on the Colorado River and an
additional 117 miles on the Green River), and includes measured
contributions from upstream reaches of the Colorado and Green
Rivers, from the San Rafael River, and unmeasured contributions
from 26,400 km^2 (fig. 1 and table 1).

The sediment contribution from ungaged tributaries for
Reach 2 was estimated by least square regression for the 10
years of measurement by predicting the differences, Δ, between
measured inputs and outputs by using contributions from the San
Juan River (SJ), the Paria River (PR), and the San Rafael River
(SR):

$$\Delta = HI + SJ - LF = M_1 \cdot SJ + M_2 \cdot PR + M_3 \cdot SR. \qquad (2)$$

where HI is the yearly sediment load at the Hite gaging station,
LF is the output at Lees Ferry, and M_1, M_2, and M_3 are the
estimated coefficients. (Note that the Paria and San Rafael

rivers lie, respectively, downstream and upstream from the drainage
area of Reach 2, but they drain predominantly desert areas that
should be representative of the nearby ungaged tributaries to
Reach 2.) This regression, with estimated M_1, M_2, and M_3 values
being .34, .92, and 2.04, respectively, explains 46 percent of the year-
by-year differences (Δ's) and implies an average sediment yield
from ungaged tributaries of 524 metric tons/km^2-yr. The estimated
yearly changes in sediment storage within Reach 2 are therefore
the residuals from the regression (fig. 3). A similar procedure
was used for Reach 1 using the San Rafael, San Juan, and Paria
River contributions as estimates of the sediment yield of the
ungaged tributaries, explaining 54 percent of the variation and giving
an estimated average sediment yield for the ungaged tributaries
of 376 metric tons/km^2-yr.

Because of the relatively high contributions from ungaged
tributaries in Reaches 1 and 2 and because of the necessity to use
estimates based partly on measured contributions for drainage
basins outside the reach in question, the estimated storage changes
for these reaches are not as accurate as for the Upper Canyon;
however, the very similar patterns of estimated storage changes
among the three reaches (fig. 3) suggests that the estimates are
reasonable.

Within the Upper Canyon, the basic pattern of storage changes
in response to discharge and sediment input variations is essentially
the same for the range of possible values for M discussed above.
In figure 2 monthly values of discharges, change in sediment
storage, and bed elevations of the Grand Canyon and Lees Ferry

gaging stations have been averaged over the pre-dam decade from
1948 through 1957 to show seasonal patterns of storage changes
and scour and fill behavior; figure 3 summarizes yearly variations
in peak discharge, average bed elevations, and estimated changes
in sediment storage over the years of record from 1922-1970
(storage changes could only be estimated for the period from 1948
through 1970, years for which suspended level measurements were
taken from the Little Colorado and Paria rivers).

During the unregulated years from 1948-57 and the years
marginally affected by dam construction (1958-62), the large
May-June flood peaks from mountain snowmelt runoff eroded much
bed and bank sand from the Upper Canyon, resulting in large net
sediment removal or negative storage (fig. 2). The flood peak
net storage loss averaged about 10.3×10^6 metric tons/yr during
the years 1948-57 (fig. 2) with a peak value of 22.6×10^6 in
1957, corresponding to values of bed scour throughout the Upper
Canyon of approximately 0.7 and 1.5 m respectively (see
discussion below). On the average, this loss of sediment was
made up for by inputs from desert tributaries, including the
Paria and Little Colorado rivers during the rest of the year,
particularly during the summer thunderstorm season from July
through September (fig. 2). Also adding to this accumulation was
the lower transport capacity at the Grand Canyon gaging station
than at the Lees Ferry gaging station during low flow months
(fig. 4).

The magnitude of sediment storage or removal accompanying
flood-stage runoff is affected by the past history of storage

changes. For example, past episodes of pronounced scour led to lower velocities for a given stage, tending to reduce future scour associated with high discharge and, conversely, encouraging deposition during tributary floods. The month-by-month record of sediment transport reveals several types of history-dependence in storage changes:

1) If two consecutive months have nearly equal flood peaks, the first removes much more sediment from the Upper Canyon than does the second. This produces a strong hysteresis during flood peaks with stronger net sediment removal during the rising stage. In cases similar to those of the periods 1948-49 and 1950-51 where flood peaks of similar magnitude occurred in successive years without substantial intervening contribution from tributaries, the second peak removes much less sediment (fig. 3).

2) Strong net scour can occur during a moderate flood peak if substantial accumulation has occurred due to tributary floods since the last major spring flood peak (for example, 1956, 1962, and 1965).

3) Net sediment storage during floods of the Little Colorado and Paria rivers is greater for the first flood peak than for a second of similar magnitude if no large mainstream flood peak has intervened, as during 1963-64 and the two tributary floods in 1951.

Patterns and cause of scour and fill --Scour and fill from a cross section may occur through two processes: local redistribu-

tion of bed sediment among reaches, and net storage changes through long segments of the river. The former will be termed "local" processes, and the latter "general". Recent research particularly by Colby (1964) and Lane and Borland (1954), suggests that general processes are rare in short-term scour and fill in natural streams due to the large volumes of sediment storage changes necessary to produce appreciable bed elevation changes over long reaches. Thus they suggest that observed scour and fill is due primarily to local causes. The extreme scour and fill behavior of the Colorado River in the Grand Canyon was documented by Leopold and Maddock (1953, p. 33-43), and Leopold, Wolman, and Miller (1964, p. 227-241). They suggested that the observed scour and fill is due to changes in bed roughness with stage rather than changes of energy gradient within the reach.

The present study suggests that observed scour and fill behavior in the Colorado River within the Grand Canyon is due to a complex combination of short-term local processes and general processes acting over a longer time scale of weeks, months, or years. The importance of the general processes is documented by the large sediment storage changes in the Upper Canyon which sufficiently account for the year-to-year variations in bed elevations of the magnitude observed at the Grand Canyon and Lees Ferry gaging stations and which correlate closely with these bed elevation changes (see discussion below). Also, the similar patterns of year-to-year sediment storage changes in the three reaches representing several hundred miles of the Colorado River (fig. 3) indicate river-length general processes of scour and

fill. On the other hand, the importance of local processes is indicated by the opposite reaction of the two gaging stations to the passage of the spring flood peak (the Grand Canyon cross section initially filling, and the Lees Ferry scouring), such that, in the case of the Grand Canyon cross section, the month-by-month fluctuations in bed elevation are nearly opposite to changes that would be expected from net storage changes (fig. 2).

Local scour and fill --Local processes of scour and fill may include one or more of the following mechanisms:

1) Narrow channel sections tend to scour during rising stages and fill during waning flow, with the bed sediment displaced during the rising state accumulating downstream from the constriction (Colby 1964, Silverston and Laursen 1976, Andrews 1979).

2) Migration of bedforms through gaging station cross section can cause irregular variation of bed elevation (Foley 1978).

3) The supercritical control exerted by fixed-bed rapids may cause net scour or pools upstream from the rapids during high stages, with possible accumulation at the head of the next pool downstream (Silverston and Laursen 1976).

4) Increased turbulence generated by rapids during flood stages may scour the pool immediately downstream, with possible concomitant fill further downstream in the same pool if it is sufficiently long. The scouring potential of the rapids is indicated by the numerous

sand-floored deep pools found throughout the canyon.

During high stages these pools may deepen and elongate,

and adjacent channel banks may be eroded where composed

of sand and silt. Adding to this effect is the increased

energy gradient and bed shear through pools at high

stages (Keller 1971, Richards 1976, Lisle 1979).

The second mechanism will generate short-term irregular changes

in bed elevation. Although such irregularity may occur, the

pattern of changes experienced by both the Grand Canyon and Lees

Ferry gaging stations, although different in their relationship

to stage, nonetheless show a consistent year-to-year pattern

(fig. 2). Silverston and Laursen propose that the "weir effect" of

rapids (mechanism three) should show complex, almost unpredictable

patterns of scour and fill, certainly from one gaging station to

another, but also presumably through time at any single gaging

station due to routing of supplied and scoured sediment from one

pool to another. However, such local routing effects are probably

overshadowed by the scour and fill caused by net storage changes

and mechanism one above, because of the observed regularity of

scour and fill.

The fourth mechanism--scour due to turbulence generated in

rapids--has apparently gone unrecognized and seems capable of

explaining not only local variations in scour and fill behavior

and the observed month-to-month changes in net sediment storage,

but also general patterns of scour and fill and the net storage

increase that has occurred since the construction of the dam.

In its local effect, rapids act much like a local channel

constriction, except that the locus of maximum scour is displaced

downstream due to the inerodible bed in the rapids proper. The anomalous behavior of the Grand Canyon gaging station--filling during rising stages and excavating during falling and low water stages--is probably due to its location at the lower end of a long pool below the rapids. Scour of the pool during rising stages is probably accompanied by temporary fill further down-stream at the gaging station where the rapids-generated turbu-lence has dissipated.

On the other hand, the Lees Ferry gaging station is located in a local constriction, leading to the classic pattern of scour during rising stages and fill during waning flows by mechanism one. *General Scour and Fill* --The long term, general process of scour and fill at the Grand Canyon gaging station very closely follows the pattern of sediment storage changes in the Upper Canyon (fig. 3), and is of the correct order of magnitude for the changes of bed elevation throughout the Upper Canyon that would be esti-mated from storage changes. The Lees Ferry gaging station varied less in bed elevation than the Grand Canyon gaging station prior to 1959, and the pattern of bed elevation changes paralleled more closely storage changes in Reach 2 than those in the Upper Canyon.

Throughout the Upper Canyon from below Lees Ferry the river is characterized by numerous rapids (the 225 miles below Lees Ferry has an average gradient of .0016), whereas the 180 miles upstream, including the Lees Ferry gaging station, have very few rapids and an average gradient (.0003) of 5.3 times less than that within the Grand Canyon. This change in channel type below Lees Ferry affords an explanation for the relatively large magnitude of scour and fill occurring in the Upper Canyon as com-

pared to upstream reaches. Not only are year-by-year storage variations greater in the Upper Canyon than for Reaches 1 or 2, but the upstream reaches are twice as long with greater average channel width than the Upper Canyon, implying a lesser average amplitude of bed scour and fill in the upstream reaches.

Specifically, the large magnitude of scour during rising and high water stages within the Upper Canyon is due to the increase in turbulence generated within the rapids and the large rate of increase in velocity within the pools between rapids as the flow stage increases. Scour due to turbulence should also persist further downstream within pools during flood discharges. This scour is not localized to the few rapids closest to Lees Ferry, but is distributed throughout the canyon, explaining the high correlation of the average bed elevation of the Grand Canyon gaging station to yearly changes in storage (fig. 3 and table 2). The reason for the distributed scour is the finite time period (days or weeks) required to scour the bed until velocities are reduced to values that produce an equilibrium between sediment input and output. During rising stages, bed material transport falls short of capacity throughout the Grand Canyon, and scour occurs (with local exceptions due to other short-term mechanisms of scour and fill, such as at the Grand Canyon gaging station). This tendency for net scour during high flows and net deposition during low flows is further attested by comparing suspended sediment transport (monthly values) for the two gaging stations for months without appreciable sediment input from tributaries (fig. 4).

The strong correlation of long-term changes in bed elevation with estimated changes in sediment storage provides confirmation of the accuracy of the estimated storage changes and a criterion for selecting the optimum value of the weighting factor, M, in Equation 1; the yearly average storage in the Upper Canyon correlates most closely with yearly average bed elevation of the Grand Canyon gaging station for a value between about .30 to .35 (fig. 1 and table 2). The bed elevation changes, ΔE, resulting from changes in sediment storage, ΔS, in the Upper Canyon is a function of the length of the canyon between Lees Ferry and Grand Canyon (140 km), the proportion of the total channel length that is sand bed, P, the average channel width, W, and the density of the sediment, D:

$$\Delta E = K \Delta S, \text{ where } K = \frac{10^6}{140,000 \ D \times P \times W}, \tag{3}$$

and E and W are measured in meters, ΔS is in metric tons $\times 10^{-6}$, and the density is measured in metric tons/m^3.

Assuming that the average channel width is about 95 m (depending upon stage), the sand bed density about 1.5 metric tons/m^3, the proportion of sand bed about .75, then the constant, K, should have a value of about .066. A regression predicting average yearly values of bed elevation at the Grand Canyon gaging station from average yearly sediment storage in the Upper Canyon (table 2) has a slope, or estimated K value, of about .054 for the value of the weighting factor, M, (.3) with the highest correlation (r=.91). This close correspondence between the predicted proportionality for the Upper Canyon and the observed proportionality for

the Grand Canyon gaging station further confirms that the long-term
changes in bed elevation at this cross section are representative
of bed changes throughout the Upper Canyon.

Effect of Glen Canyon Dam on the Sediment Budget --In general,
marked changes in discharge characteristics or sediment loads cause
large alterations in channel characteristics such as width, depth,
gradient, roughness, and bed elevation. The imposition of a dam
on a suspended-load, dominantly sand-bed channel, in general causes
profound changes downstream. For example, at the Yuma, Arizona
gaging station on the Colorado River, 350 miles downstream from
Lake Mead, the drastic decrease of sediment coupled with flow
regulation caused net bed scour, with accompanying channel narrowing
and deepening (Leopold and Maddock 1953, p. 37-39).

The changes in hydraulic regime below a dam are partly off-
setting; the drastic reduction in bed-material load (tending to
cause net scour) is opposed by the effect of flow regulation, which,
by eliminating flood peaks, reduce transport capacity. Generally
the former offsets the latter, leading to net scour as at Yuma.
Straightforward application of sediment transport relationships
suggests the same should have occurred in the Grand Canyon.

At the Grand Canyon gaging station the sediment load was
reduced by the dam by a factor of about 3.9. Further upstream
the reduction is greater, the factor being about 15 just below the
entrance of the Paria River. Pre-dam and post-dam flow duration
curves (daily averages for the slowly-varying pre-dam flows and
two-hourly averages for post-dam conditions) can be used to
estimate relative total transporting power of the pre- and post-dam

flows if the following is assumed:

1) that bed-material load capacity is proportional to the 1.8 to 2.0 power of the discharge, consistent with several suspended load transport formulas (See Howard 1980) and,

2) that changes in channel width and gradient since the dam have been negligible.

A reduction of transport capacity by a factor of about 1.7 to 2.1 would be predicted.

Such considerations led Dolan et al. (1974) and Laursen et al. (1976) to predict net scour of sand below the dam throughout the Grand Canyon. Indeed, at the Lees Ferry gaging station and other cross sections in the 15 miles between this gaging station and the dam, scour has been dramatic to the extent that coarse bed armoring has developed (Pemberton 1976). However, the bed armoring ceases below the entrance of the Paria River 15 miles below the dam. In addition, the bed elevation of the Grand Canyon gaging station has increased, and sediment budgeting strongly suggests a net storage increase throughout the Upper Canyon since the beginning of complete flow regulation in 1965 (fig. 3).

The final peak discharge of 1800 m^3/s in 1965 prior to closure of the diversion tunnels at Glen Canyon Dam caused a large net scour throughout the Upper Canyon. From that time until cessation of suspended sediment recording in 1970 there was net storage, corresponding to an estimated average bed aggradation within the Upper Canyon of 1.8 to 2.6 m, for estimated values of the factor,

M, between .3 and .45, respectively. Correspondingly, average bed elevations at the Grand Canyon gaging station increased by about 1.9 m from the end of 1965 to the end of 1970 (fig. 3), reaching a record gage height for the period of measurement starting in 1922. Approximately .6 - .7m of this aggradation may have been due to a stage rise of the same magnitude as that at the gaging station due to the debris accumulation at the tributary fan of Bright Angel Creek, which was subjected to a catastrophic flash flood in December, 1966 (Cooley et al. 1977).

Although post-dam aggradation within the Upper Canyon runs counter to the predictions using straightforward application of bed material transport formulas, the aggradational behavior follows pre-dam patterns; the post-dam flow regime is most similar to pre-dam low-water discharges, during which aggradation occurred due to sediment supplied by tributary floods. Thus, due to the lack of the flushing action of turbulence generated by pre-dam flood peaks, sand has accumulated rather than scoured, except very close to the dam as at the Lees Ferry gaging station. The failure of bed material transport equations to predict the observed post-dam deposition within the Upper Canyon appears to be due in part to the assumption of a constant energy gradient (which, in reality, should increase with stage in the pools) and in part to the variation in rapids-generated turbulence with stage.

Because of the lack of sediment records after 1970, long-term trends in sediment storage cannot be monitored. Bed elevation changes at the two gaging stations have been relatively small since 1968, but have been opposite in trend to the large immediate post-dam

changes (fig. 3). At Lees Ferry, the initially strong degradation (about 3.4 m) has been followed by a slight recovery (about .7 m), and the bed is now about 1/3 covered by slowly-migrating sand dunes (personal communication, William B. Garrett, U.S.G.S., Tucson, Arizona). The source of this sand may be continued erosion of pre-dam terraces, but the present sand bed suggests that the complete scouring of these terraces (at least to an immobile pavement) may take many years, even immediately below the dam. Also, the post-dam scour has apparently reduced the bed elevation to the extent that sand transport rates are very low, particularly in sections just upstream from fixed control points at rapids. The recent degradational trend at the Grand Canyon gaging station of .4 m since 1968, may be due to larger peak releases from Lake Powell in the last few years, coupled with occasional winter flooding of the below-dam tributaries.

Part of the net sediment accumulation within the Upper Canyon may not be on the bed, but may have been deposited on low overbank terraces during occasional peak flows as well as by eolian deflation of sand exposed on the beaches during the diurnal low water (Dolan et al. 1974). In addition, buildup of some of the tributary fans due to addition of debris during flash floods may have caused local aggradation due to the backwater effects. Howard and Dolan (1979) estimate that 25 percent of the fans have had sufficient tributary deposition to noticeably narrow the main stem. However, given the magnitude of post-dam sediment storage, it seems unlikely that any or all of these alternative sinks can account for much of the post-dam storage. General channel aggradation must also have occurred.

An attempt was made to detect post-dam bed changes by comparison of depth sounding records made in 1976 with those made in 1965 by Leopold. Leopold made depth observations at 1/10 mile intervals throughout the canyon, whereas our records were continuous (Dolan et al. 1979 Approximately 50 miles of channel composed of six sections of relatively narrow canyon (to minimize stage-dependent width variations) scattered throughout the first 225 miles below Lees Ferry were used in this comparison. Our records were sampled at 1/10 mile intervals, although exact matching with Leopold's sample was not possible. Because the post-dam flows vary diurnally within wide limits, discharges at the time of measurement were determined by flow routing from the Lees Ferry or Grand Canyon gaging stations. Due to the considerable differences in discharge between Leopold's measurements (ca. 1,370 m^3/s) and ours (168 to 517 m^3/s), post-dam aggradation could be detected only indirectly. One indication would be if the rating curve for depth as a function of post-dam discharges would predict shallower depths than those that existed for the Leopold measurements. In figure 5 a logarithmic regression line through the 6 post-dam reach average points falls within 1 m of the average of Leopold's depth data in the same reaches.

Another indication of aggradation might be a decrease in variance of depths since the dam, because much of the post-dam aggradation has presumably been in decreasing either the depth or length of the below-rapids scour holes. Although the post-dam depth data show a smaller variance than do the Leopold data for 5 out of 6 study sections, the difference is small and not statistically significant, particularly since the Leopold data was collected in a different manner. The depth variations with discharge have nearly

the same exponent as the station depth discharge rating curve for
the Grand Canyon gaging station (after Williams 1978), which
indirectly verifies that this gaging station is typical of narrow
channel sections within the canyon. Thus the post-dam channel
depths seem to be consistent with the measurements made by Leopold
in 1965 (after correcting for stage difference) but the measurement
errors are too large to distinguish average bed elevation changes
of the magnitude suggested by changes in storage (about 2 m).

One set of data seemingly contradicts the conclusion of net
post-dam aggradation in the Upper Canyon. If, in fact, the post-
channel bed were higher than normal pre-dam levels, for a given
discharge, its sediment yield should be higher, at least during
those times when desert tributaries were not directly contributing
fine-grained suspended or wash load. However, quite the opposite
is true. For a given overall monthly discharge, the sediment yield
of the Grand Canyon gaging station has decreased by a factor of
about 13 since the last high discharges of 1965 (see figure 4: a
similar decrease is apparent also in the daily discharge sediment-
load relationship). In addition, there did not seem to be any trend
towards increasing sediment discharges during the period from 1966-
1970 when channel beds were apparently aggrading in the Upper Canyon.
Several possible reasons for the low post-dam sediment yields may
be advanced:

1) The bed of the Upper Canyon has, in fact, been scoured.

2) The average grain size of the bed and banks has increased,
   reducing sediment yields. Limited bed sampling at the
   Lees Ferry and Grand Canyon gaging stations suggest a
   post-dam increase in average grain size of the bed by a

factor of 1.6.

3) Some of the apparent post-dam storage of sediment has gone into overbank deposition or deposition behind aggraded rapids.

4) Due to the rather limited range of post-dam discharges, the channel bed has been remolded by selective scour until it minimizes sediment yields for the post-dam discharge range. During the widely varying range of pre-dam discharges, the constant reshaping of the bed at different discharges, never permitted this equilibration.

5) Low-water, pre-dam discharges of the Colorado River within the range of post-dam discharges included large amounts of very fine sand and silt derived from reworking of bed and bank deposits left during waning flood stages.

6) Post-dam sediment discharges at the Grand Canyon gaging station may have been underestimated, due to the daily fluctuation in discharge and the limited sampling (usually once a day).

7) Net channel widening due to post-dam scour of beach deposits has reduced velocities for a given discharge.

Because various lines of evidence suggest net deposition rather than scour, the first explanation seems unlikely. Explanations 3, 6, and 7 are probably quantitatively insufficient, so that one or more of explanations number 2, 4, and 5 probably account for the post-dam sediment yields.

In conclusion, our studies indicate that the sand bed of the Colorado River in the Grand Canyon under the natural regime was subject to seasonal cycles of general scour and fill occasionally

exceeding an average amplitude of 2 m along the entire canyon.
In pools below rapids and in narrows, local scour and fill may be
several times the average. Severe floods (a peak flow in 1884
may have exceeded 8500 m^3/s) may scour to much greater depths, as
evidenced by a sawn board buried by 15 m of sand and gravel at the
Hoover Dam site (Bureau of Reclamation 1950). The uppermost 2 to 6
m of sandy alluvial fill on the bed (Bureau of Reclamation 1950,
1960, Pemberton 1976) is probably reworked by the frequent spring
flood peaks in the range of 2500 to 3400 m^3/s, whereas the underlying
4 to 40 m of gravelly sands probably are moved only by the more
intense floods that also rework the cobble bars. Greatly reduced
flood peaks since completion of Glen Canyon Dam have decreased the
turbulence generated by rapids to the extent that an average of more
than 1.5 m of sand has accumulated on the bed of the Upper Canyon.

DISCUSSION AND CONCLUSIONS: TIME SCALES AND CONSTRAINTS ON EQUILIBRIUM

All rivers share the tendency toward balancing of input and
output of sediment through self-adjustment of their morphology,
a tendency described as "quasi-equilibrium" by Leopold (1969, p. 236).
Any discussion of fluvial equilibrium must therefore include the
definition of the elements to be examined for equilibrium (for
example, supply and removal of sediment of a particular size range),
the characteristic time scales of adjustment (rates of transport
and comminution), the past history of system inputs (supply of
sediment), and the constraints affecting the system response (fluvial
morphology). Of these the characterization of system structure and
operation (the constraints) seems least discussed within the context
of equilibrium, yet these constraints are one of the most obvious

aspects in the balance of sediment flow through a canyon and the resultant fluvial morphology.

The major constraint on fluvial transport, both directly and indirectly, is structural control. As noted previously, in the Grand Canyon the extent of these constraints varies from the severely restricted channel width and alluvial fan development in Granite Gorge to minimal effect in the broad valley in the Upper Canyon. Where the channel is narrow, transport capacity and particularly competency are enhanced relative to unconfined channels. Indirectly, structural control by canyon walls is important in providing the sources of alluvial fan debris.

Sediment transport through the Grand Canyon involves complex interactions between the grain sizes in transport, each with its own characteristic time scale of supply and removal. The transport and deposit of each grain size in turn form constraints on the transport of other size ranges of sediment.

Because most of the drop in the river occurs in rapids where debris is contributed by tributaries and rockfalls, the overall river gradient is primarily determined by the balance between addition and removal of coarse debris. The rate of addition depends upon the size, quantity, and location of the supplied debris together with the frequency of tributary flooding or rockfall. The rate of removal depends upon the in-situ comminution of the boulders to a transportable size by abrasion, breakage, and chemical weathering. This equilibrium is statistical rather than exact, for both addition and removal of alluvial fan debris occurs sporadically during floods. The characteristic time scale of this balance of addition and removal must be on the order of a thousand years or more. The most

distinguishing feature of the equilibrium of fan debris is that the balance is not, as in the case of fine sediment, between sediment input and its unmodified transport out of the system, but rather between input and weathering or erosion to a finer grain size.

The morphological context of the debris-fan rapids along with the structurally controlled channel width constitute the major constraints upon transport and deposition of cobbles. The cobble bars, reworked primarily during major floods, have an intermediate time scale of adjustment, probably measured in hundreds of years. Both comminution and downstream transport are involved in the balance of removal of gravel and additions are derived both from upstream and locally from tributary floods, rockfall, and comminution of fan debris. The fans, bars, and channel width constraints, in turn, provide the morphological framework for transport and deposition of fine sediment.

Despite the large seasonal epicycles of scour and fill, the Lees Ferry and Grand Canyon gaging stations maintained essentially constant bed elevations during the period from initiation of measurements in 1922 until after completion of Glen Canyon Dam. This suggests a rough equilibrium of addition and removal of fine sediment from the portions of the bed and banks floored with fine alluvium, with a time scale for establishment of equilibrium measured in a few months.

Although the deposits of coarser debris act primarily as constraints on transport and deposition of finer sediment, there is some reverse influence. A complete cut-off of sand delivery within the natural river regime would probably cause sufficient scour to require readjustment of the debris fans and cobble bars.

Leopold (1969, p. 135) has suggested that rivers, such as the Colorado River in the Grand Canyon, tend to adjust their gradients and other morphological features for transport or supplied sediment with the least work or greatest efficiency. This least-work hypothesis for fluvial features has been successfully applied by several geomorphologists, and most directly for sediment transport by Kirkby (1977). However, the existence of morphological constraints may severely limit the efficiency of transport (Chang 1979). The overall channel gradient is dominated by the fall in rapids, so that the river profile is not primarily adjusted for transport of the most abundant size components; that is, sand and finer sizes. Thus, due to the numerous rapids and the narrow channel width, the Colorado River is over-efficient with respect to transport of sand (by contrast, the former low gradient of the river system upstream from Lees Ferry suggests that that section was, in fact, adjusted primarily for sand transport). Finally, the concept of least work is inapplicable to the wash load, for which there is excess transport capacity.

Although the detailed suspended sediment records indicate that input and output of sand-sized sediment were roughly balanced in the natural river regime, the time scales of adjustment of the tributary fans and the cobble bars is too long to ascertain whether addition and removal have been in balance during past decades, particularly since the influence of Quaternary climatic changes is likely to have had a remnant influence on the rapids' morphology.

The Quaternary morphology of the river is uncertain due to limited alluvial deposits in the narrow canyon. Alluvial fans and

attendant rapids may have been either more or less frequent, or
possibly both in alternation, because the enhanced scouring potential
of the glacial meltwaters may have been balanced by increased
physical weathering of the canyon walls. The extent of flash flood-
ing in tributary canyons during pluvial episodes is also uncertain.
In some locations sand and gravel deposits extend 200 or more feet
beneath present bed levels (Bureau of Reclamation 1950) suggesting
that deep scour occurred occasionally during the Quaternary, proba-
bly associated with diminished development of tributary fan rapids.
Scattered gravel terraces occur along some of the wider portions of
the Upper Canyon, and these probably correlated with the extensive
development of pluvial gravel terraces of Quaternary and Tertiary
age farther upstream along the Colorado River and its tributaries.

The influence of Glen Canyon Dam on the equilibrium of sedi-
ment transport and fluvial morphology is occurring over the same
range of time scales that is characteristic of the various grain
size ranges. The transport of sand and the sandy alluvium have
responded most rapidly and most completely to the diminished
sediment delivery and diminished flood peaks. The net effects have
been moderate, with slight lateral erosion of terraces and apparent
net sedimentation on the bed. The characteristically rapid response
of the sandy deposits of the Colorado River to change in supply or
discharge suggest that future changes will be slight as long as the
pattern of release remains the same. However, there has been a
proposal to widen the range of daily variation of releases from the
dam to enhance peak power generation, with minima near 1,000 cfs
and maxima near 40,000 cfs. Although under the present pattern of

release the diminished turbulence has more than compensated for reduced sand supply, the proposed increased maximum discharges will considerably enhance transport capacity as well as bring additional terrace deposits within the zone of inundation, so that appreciable scour can be expected. The wider range of discharge will also greatly enhance drawdown effects on the sedimentary terraces, increasing ground water sapping and possibly creating bank instabilities.

The effect of Glen Canyon Dam upon the tributary alluvial fan rapids has been felt more slowly and sporadically, since rapids in equilibrium with pre-dam discharges are stable under present flows, but debris deposited by post-dam tributary flooding is stable at steeper gradients and with a narrower channel. An aerial photographic study suggests that about 25 percent of the alluvial fans along the canyon reach were noticeably enlarged from 1964 to 1973 (Howard and Dolan 1979), many probably associated with several intense thunderstorms during December, 1966. The same trend of steeper, narrower rapids as well as formation of new rapids will probably continue throughout the lifetime of Glen Canyon Dam due to the slow time scale of readjustment. As individual rapids are steepened by tributary flooding, the sand bed will in consequence readjust, aggrading above the rapids and possibly scouring below. These long-term sand-bed readjustments are secondary responses superimposed upon the rapid primary response to the dam (Howard 1965).
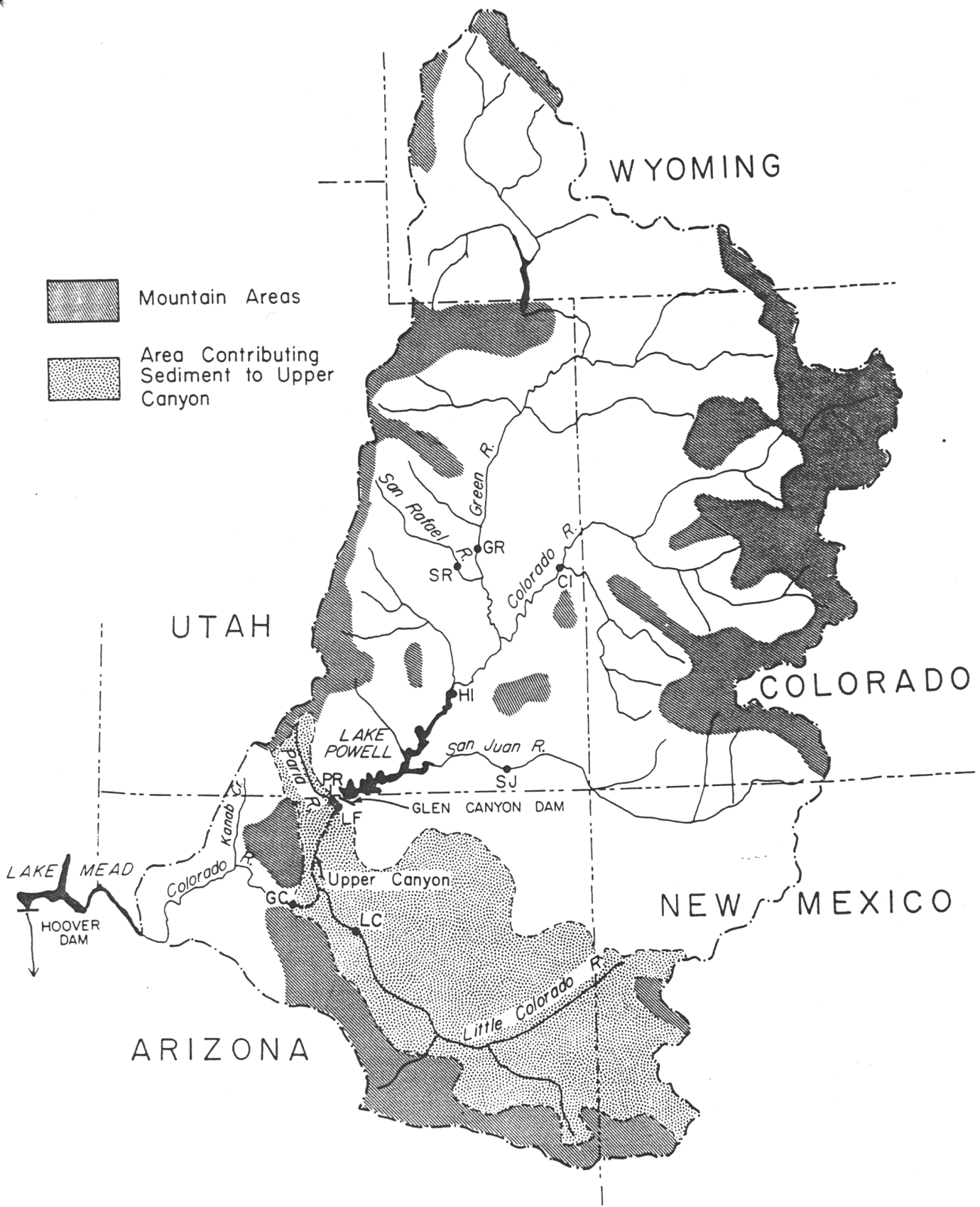
Figure 1. The Colorado River basin above Lake Mead. Snowmelt in mountain areas produces the yearly spring flood peak, but most sediment is contributed from the desert areas (unpatterned or dotted) by summer thunderstorms. Gaging stations identified as follows: GC = Colorado River at Grand Canyon; LF = Colorado River at Lees Ferry; LC = Little Colorado River at Cameron; HI = Colorado River at Hite; PR = Paria River; SR = San Rafael River; SJ = San Juan River at Bluff; GR = Green River at Green River, Utah; CI = Colorado River at Cisco.
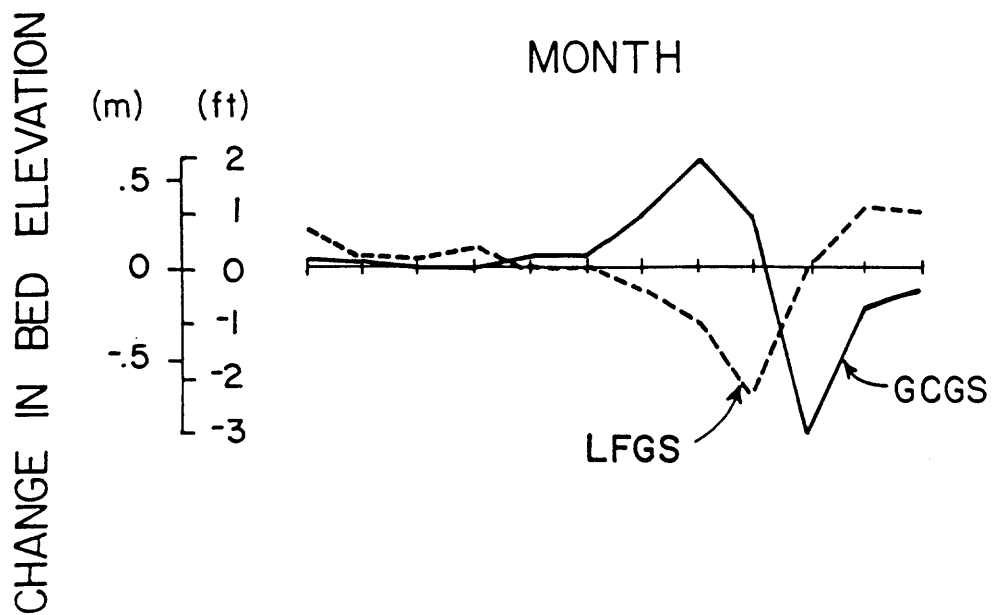
Figure 2. Changes in monthly averages of discharge, sediment storage, and bed elevations of gaging stations for the Upper Canyon section of the Colorado River in the Grand Canyon. Values represent averages for the 10-year period beginning in October, 1947. GCGS = Grand Canyon gaging station; LFGS = Lees Ferry gaging station.

Figure 3. Yearly variation in 1) peak discharge, 2) average gaging station bed elevations, and 3) estimated average values of sediment storage for the Upper Canyon section of the Colorado River in the Grand Canyon. Year-end values of sediment storage are shown for two upstream reaches (Reach 1 and Reach 2) with the origin displaced by +20 tons x 10^{-6}. GCGS = Grand Canyon gaging station; LFGS = Lees Ferry gaging station.

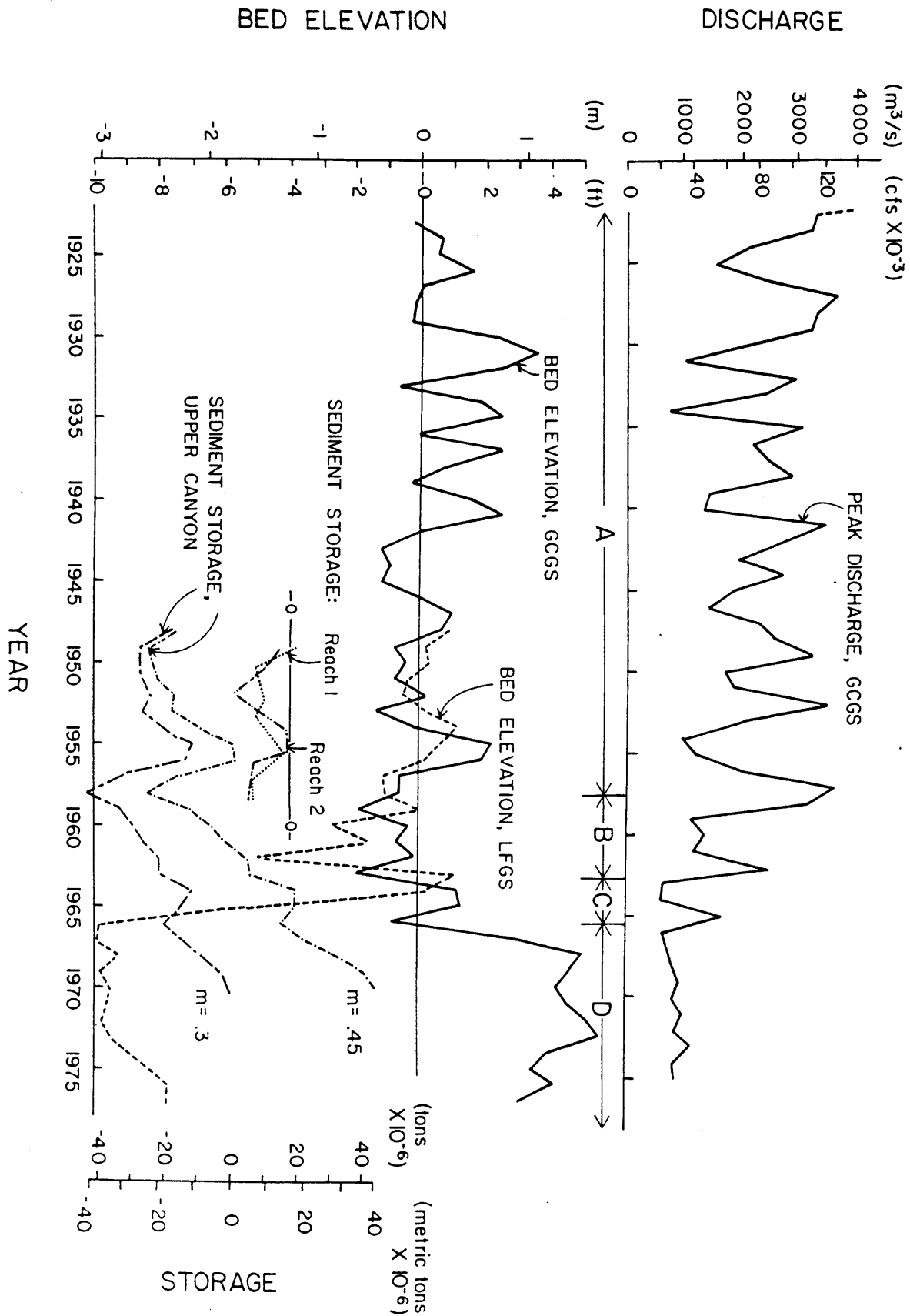Figure 4.   Relationship between monthly values of sediment load and discharge for the Grand Canyon (GCGS) and Lees Ferry (LFGS) gaging stations for the period from October, 1947 to October, 1970. Values are shown only for the Grand Canyon gaging station and for those months when the desert tributaries (Little Colorado and the Paria River) contributed negligible sediment to the river. The solid line shows a broken regression line fit to the pre-regulation months for the Grand Canyon gaging station and the dashed line is a similar relationship for the Lees Ferry gaging station.

Figure 5.   Relationship between channel depth (measured from depth soundings) and discharge for rock-confined sections of the Colorado River in the Grand Canyon. Pre-dam data taken in 1965 and furnished by L. B. Leopold (personal communication), and post-dam data from a 1976 float trip. Each point represents the average of from 29 to 192 measurements spaced at 1/10 mile intervals for six study sections located along the 225 miles from Lees Ferry to Diamond Creek, and each post-dam average has a corresponding value for the pre-dam measurements. The regression line is fit to the post-dam averages, showing the close agreement to the pre-dam measurements at higher discharge.

Mountain Areas

Area Contributing Sediment to Upper Canyon

WYOMING

UTAH

COLORADO

NEW MEXICO

ARIZONA

San Rafael R.

Green R.

Colorado R.

GR

SR

CI

HI

LAKE POWELL

San Juan R.

SJ

PR

LF

GLEN CANYON DAM

Paria R.

Kanab Cr.

Colorado R.

LAKE MEAD

HOOVER DAM

GC

LC

Upper Canyon

Little Colorado R.

BED ELEVATION

DISCHARGE

(m³/s)

(cfs X 10⁻³)

PEAK DISCHARGE, GCGS

BED ELEVATION, GCGS

BED ELEVATION, LFGS

SEDIMENT STORAGE:

Reach 1

Reach 2

SEDIMENT STORAGE,
UPPER CANYON

m=.45

m=3

YEAR

(tons X 10⁻⁶)

(metric tons X 10⁻⁶)

STORAGE

MONTHLY TOTAL SEDIMENT LOAD

(metric tons
X10⁻⁶)

(tons
X10⁻⁶)

0.1

1.0

10

100

.01

.1

1

10
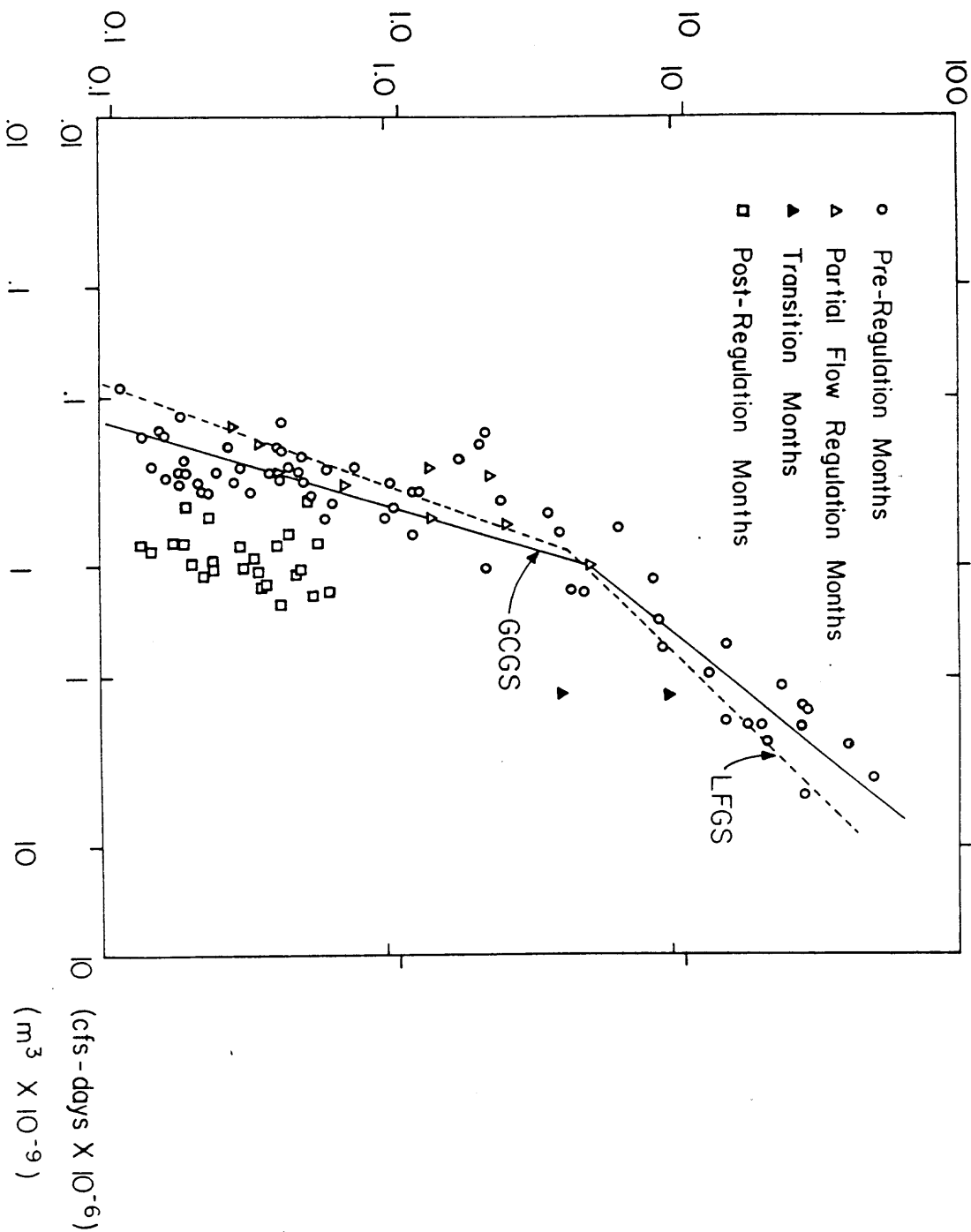
MONTHLY TOTAL DISCHARGE

o   Pre-Regulation Months

△   Partial Flow Regulation Months

▲   Transition Months

□   Post-Regulation Months

GCGS

LFGS

10   (cfs-days X 10⁻⁶)
(m³ X 10⁻⁹)

AVERAGE CHANNEL DEPTH

DISCHARGE

(m) 50 10 5

(ft) 100 50 10

D = 1.04 Q.35

x   PRE-DAM   DATA (1965)
⊙   POST-DAM   DATA (1976)

10   100   5,000   500   10,000   1,000   50,000   100,000

(cfs) (m³/s)

TABLE 1: Sediment Yields, Runoff, and Drainage Areas of the Colorado River and Tributaries
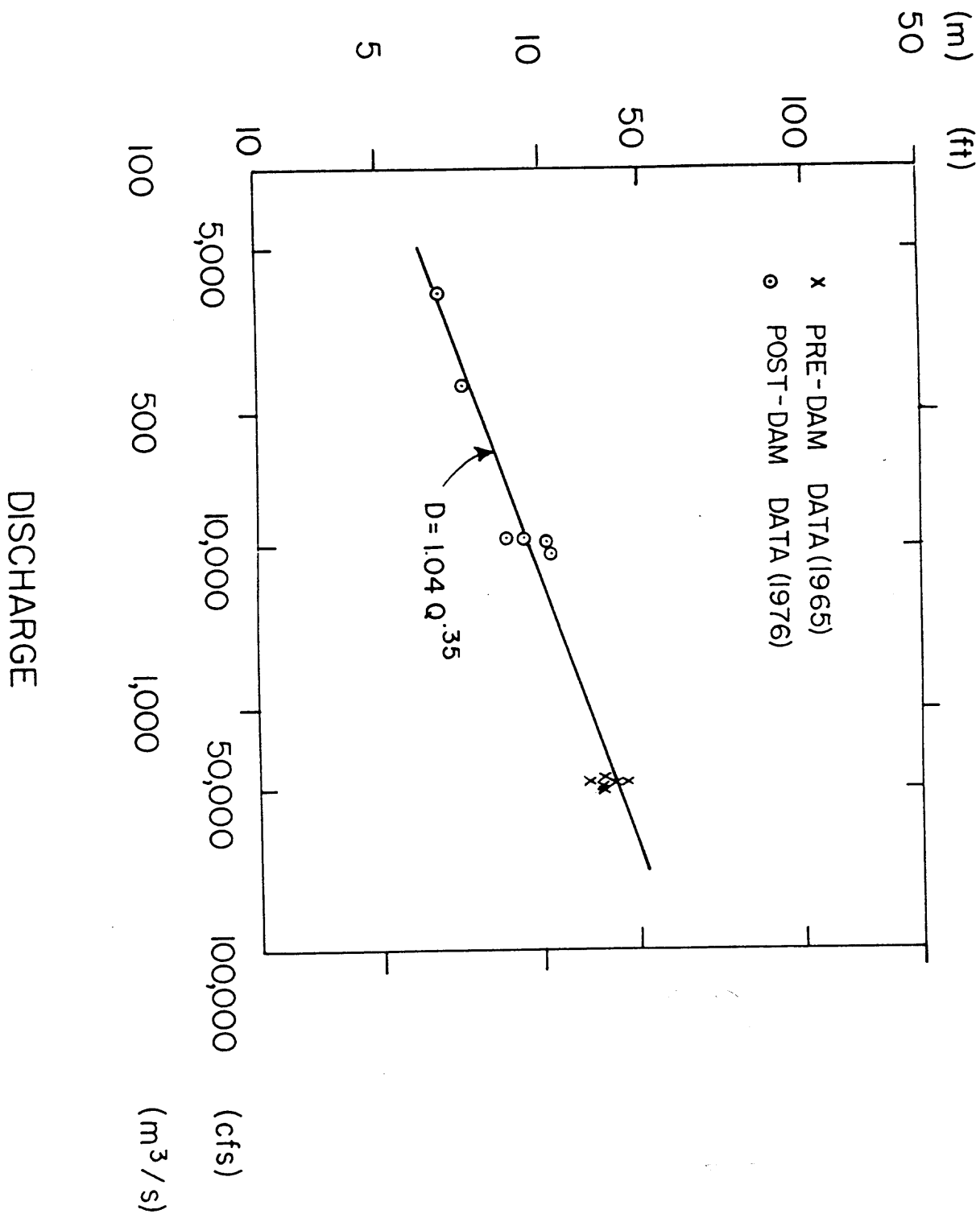
Tributary	Drainage Area (km²)	Sediment Yield (metric tons/km²-yr)	Annual Runoff (m³/km²-yr)
Reach 1			
Colorado River above Cisco, Utah	62,400	142	102,000
Green River above Green River, Utah	105,200	148	52,200
San Rafael River	4,400	298	31,100
Ungaged Tributaries	26,400	376*	----
Reach 2			
Colorado River above Hite, Utah	198,400	185	60,100
San Juan River	59,600	291	31,300
Ungaged Tributaries	21,500	524*	----
Upper Canyon			
Colorado River above Lees Ferry	279,500	237	51,900
Paria River	4,100	784	5,900
Little Colorado River	68,600	124	2,600
Ungaged Tributaries	5,100	776*	---
Lower Canyon			
Colorado River above Grand Canyon	356,900	235	41,100
Kanab Creek	2,800	307	2,400

*Estimated value: See text.

Based upon U.S. Geological Survey records for years prior to completion of Glen Canyon Dam.

TABLE 2: Correlation Between Changes of Bed Elevation and Changes in Sediment Storage for the Grand Canyon and the Lees Ferry Gaging Stations.

Gaging Station[@]		Value of Estimating Parameter			
		M=0	M=.3	M=.44	M=.65
Grand Canyon					
1948-57	r[#]	.15	.91	.88	.71
	b[*]	.007	.054	.037	.017
1948-70	r	-.31	.83	.77	.68
	b	.010	.054	.024	.010
Lees Ferry					
1948-57	r	.66	.65	.27	0
	b	.013	.020	.007	0
1948-70	r	.74	-.53	-.80	-.83
	b	.044	-.074	-.054	-.010

[#] Correlation coefficient of yearly averages of bed elevations versus estimated yearly averages of sediment storage.

[*] Regression slope of bed elevation estimated by sediment storage. Bed elevation in meters, sediment storage in metric tons.

[@] Correlation of average bed elevations, Grand Canyon with Lees Ferry gaging station:

           1948-57   .38
           1948-70   -.64

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